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Microplastics in the Atmosphere and Their Human and Eco Risks

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6.1 Introduction

Any living organism needs to respire to produce energy, and the first phase of the breathing process is inhalation or taking up oxygen/air into the lungs. The atmospheric air – the mixture of gases surrounding the planet earth – must be clean or unpolluted to be inhaled. Plastic, a manufactured universal item, has become a significant culprit in environmental pollution. However, now *microplastics* (MPs), fragmented particulate matter, have been identified as the most ubiquitous contaminator of land, sea, and air. Although many records are available of MPs in aquatic environments, soils, and different terrestrial ecosystems, including remote mountains and deep sea beds, interest in the atmosphere and its effect on biota is recent. This chapter will discuss MPs in the air, their impact on humans and ecosystems, and future research approaches to minimise air pollution due to MPs.

6.2 Microplastics in the Atmosphere

6.2.1 Size, Shapes, and Colours

Microplastics are plastic particles ranging from 1 μm to 5 mm in size and can be categorised as primary or secondary plastics (Hartmann et al. 2019). Typically, product types such as personal care, cosmetic and cleaning products, preproduction pellets, pharmaceuticals, and air-blasting media are considered primary plastics. Initially, these are manufactured in microscopic size. Secondary MPs are created due to wear and tear (i.e. mechanical fragmentation and slow photo and thermo-oxidative degradation) by the destruction of rough plastic fragments.

MPs found in the atmosphere are comparatively smaller than MPs from aquatic and sediment environments. In marine environments, the mean size of MPs ranged from one to a few millimetres for samples collected using nets with a mesh size of 200–1000 μm; using a smaller net mesh size (50–63 μm) has shown a mean size of <700 μm (Isobe et al. 2015; Zeng 2018). Although more minor, variation in sizes could be seen for MPs in the atmospheric samples; in a collection from Pyrenees Mountains, the primary length of plastic fibres was less than 300 μm (~50%), and a significant proportion of the MPs were identified as fragments with sizes <50 μm (70% of MPs) (Allen et al. 2019b). In Hamburg, most of the fragments were <63 μm (~60%), followed by 63–300 μm (~30%), while fibres mainly were between 300 and 5000 μm in length (Klein and Fischer 2019). Another study primarily found fibres of 200–600 μm (~40%) (Dris et al. 2016), whereas the other reported fibre lengths were 200–700 μm (~30%) (Cai et al. 2017). In Yantai and Shanghai, the primary particle size was <100 μm (Bergmann et al. 2019).

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Such results indicate that the number of MP particles decreased with increasing size (Bergmann et al. 2019; Isobe et al. 2015). MP sizes ranged from less than 100 μm to 5 mm in Tehran. Of those, 250–500 μm occupied 33.7%, followed by MPs of >1000 μm with a mean occurrence of 25.7% and a variation of 15.4–30.4% of the total MPs in dust samples. The mean occurrence of the 100–250 μm fraction was around 15.2% (Dehghani et al. 2017).

MPs in the environment appear in various shapes, including spheres, beads, pellets, foam, fibres, fragments, films, and flakes (Figure 6.1a). The differences observed in shapes could be due to the original form of the primary MPs, the degradation and erosion processes of the plastic particle surface, and residence time in the environment. It has been suggested that degraded MPs with sharp edges illustrate a recent introduction into the atmosphere, while smooth edges are associated with a considerable residence time (Hidalgo-Ruz et al. 2012; Rocha-Santos and Duarte 2017). Considering the shapes, in specific urban sites, whether outdoor or indoor, fibres dominated, with >60% of the MPs (Dris et al. 2017), but fragments dominated in other urban cities. In Hamburg, fragments were recorded as the dominant shape, contributing to 95% of the total particle numbers; only 5% were fibres (Klein et al. 2019). In remote areas, fragments were also the dominant shape (Allen et al. 2019b; Bergmann et al. 2019). In Iran, fibrous (16.9–44.3%, on average 33.5%) and granule (54.5–82.2%, on average 65.9%) were the most abundant MP shapes in street dust (Dehghani et al. 2017). The differences observed in the sizes and shapes of MPs could be significant as these can affect their aerodynamics and, therefore, atmospheric transport (Zhang et al. 2020a). Further, size and shape may be the decisive factors for atmospheric MPs, but their residence times in the atmosphere are primarily unknown and needs to be studied (Brahney et al. 2021).

MPs have been detected in the atmosphere in various colours including black, transparent, yellow, brown, tan, off-white, white, grey, blue, green, red, etc. (Figure 6.1b). Although colours are helpful in identifying potential sources of plastic debris and possible contaminations during sample preparation, the colour of a plastic particle has not been found to be an effective tool to infer the nature or origin of the MPs (Zhang et al. 2020a).

6.2.2 Chemical Composition

Various chemical compositions have been observed for atmospheric MPs in different regions. However, researchers couldn't find a connection or reason for the variability in polymer composition witnessed in atmospheric MPs. The primary polymers in the coastal city of Yantai were polyethylene terephthalate (PET) for most of the fibres, polyvinyl chloride (PVC) in certain fibres and films, polyethylene (PE) for fragments, and polystyrene (PS) for foams (Zhou et al. 2017). In Shanghai, synthetic compounds comprised 54% of the observed particles, of which

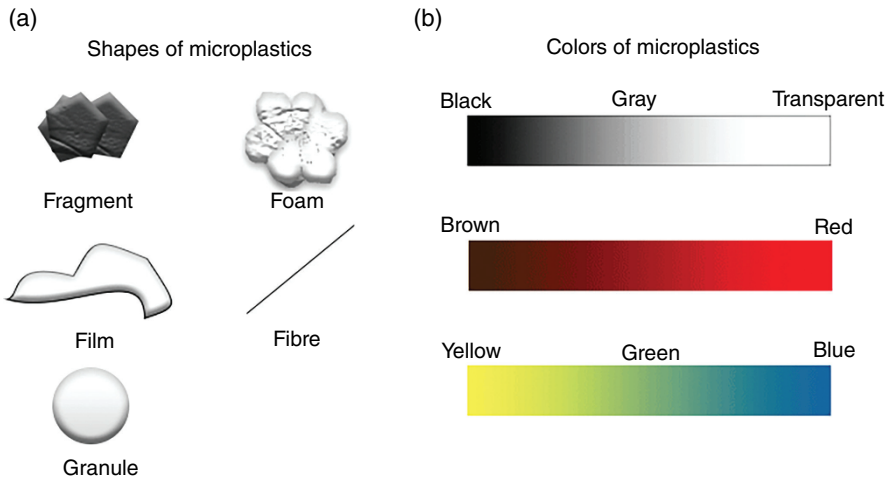

Figure 6.1 Typical shapes and colours of atmospheric microplastics. (a) Shapes of atmospheric microplastics. (b) Colours of atmospheric microplastics. *Illustration:* Ms. W.M.S.N. Bandara.

PET, PE, polyester (PES), polyacrylonitrile (PAN), polyacrylic acid (PAA), and rayon made up 91% of the MPs (Liu et al. 2019b). In Dongguan City, MPs consisted of three polymers: PE, polypropylene (PP), and PS (Cai et al. 2017). Microplastics in dust deposition from major Chinese cities were mainly determined to be PET and polycarbonate (PC) (Liu et al. 2019a). In Hamburg, Germany, 48.8 and 22.0% PE and ethyl vinyl acetate (EVA) co-polymers, respectively, dominated the atmospheric MP samples (Klein and Fischer 2019). The predominant plastic found in samples from remote areas of the French mountains was PS (as fragments), closely followed by PE (Allen et al. 2019b). Polymer types varied extensively in the Arctic snow; varnish (acrylates), plasticised rubber, and polyamides were among the most frequently identified MPs. In contrast, snow samples collected from Europe had a MP composition that was primarily (67%) polyimide, varnish, rubber, EVA, and PE (Bergmann et al. 2019).

A study of indoor air from Denmark reported the presence of MPs such as PET in the range of 59–92%, PE 5–28%, PP 0.4–10%, and nylon 0–13% (Vianello et al. 2019). However, an indoor air study from China observed PET and acrylic fibres as the significant airborne MPs (Zhang et al. 2020b). An indoor air study conducted in 12 countries measured the masses of PET and PC in MPs. According to the findings, the ubiquitous occurrence of PET-based MPs was at concentrations of 38–120 000 mg/g (median: 5900 mg/g), and PC-based MPs were at <0.11–1700 mg/g (median: 8.8 mg/g) (Zhang et al. 2019c). Among the measured MPs, PET has been recorded as the most abundant chemical (Zhang et al. 2019c).

The published data on atmospheric MPs is diverse. As described, variations can be attributed to one or many factors such as climate conditions, seasonality, morphology, or even sampling procedures and analysis techniques. However, the concentration of MPs in the atmosphere in an exact location may still depend on the local weather conditions, anthropogenic conditions, population, and topography (Batool et al. 2022).

6.2.3 Sources of Microplastics

MPs are widespread in aquatic environments, from beaches to the deep seas and oceans. Considering urban terrestrial settings, critical potential sources of MPs emissions are vehicle abrasion (mainly tyre treads), construction activities, synthetic clothes washing, upholstery, and aeolian transport of plastic debris. It could be seen that higher population densities in cities and industrialisation generate more plastic waste and litter. Researchers claim that polluted aquatic bodies and ocean waves can release MPs into the atmosphere. Furthermore, it is assumed that dust produced from agricultural lands (applying biosolids as fertilisers) is another source that discharges MPs into the atmosphere.

Road channelising devices (traffic cones, drums, and barrels) and speed bumps manufactured using recycled PVCs from bottles intensify the MP pollution in urban areas. These MPs are light enough to resuspend from landfills and urban surfaces by wind currents and traffic activities and contribute to atmospheric particulate load. The focus has shifted to MPs in indoor air and the potential emitters increasing these particles in urban areas. Plastic containers and wrapping material used in food packing are also identified as significant sources of human exposure to MPs. With the COVID-19 pandemic, the masks people use have become an important source that releases MPs into the atmosphere. Also, poor-quality masks and reused for prolonged periods can pose a higher risk of MP inhalation (Torres-Agullo et al. 2021).

6.2.4 Spatial Distribution and Rate of Deposition

MPs have been isolated from the air of cities, residential areas, and secluded areas such as mountain tops and sea beds. This means they are far from the source of origin, confirming their transport in the atmosphere. The air is a reservoir and a critical pathway that transports suspended materials within a country or worldwide. The atmosphere is subjected to various processes, e.g. wind speed and directions, up/down drafts, convection lift, and turbulence. These are important vectors that affect MP transport, which further influences the flux mechanism and source-sink dynamics of plastic pollution in diverse ecosystems (Bank and Hansson 2019; Liu et al. 2019c;

Figure 6.2 Schematic representation of the plastic cycle. *Illustration:* Ms. W.M.S.N. Bandara.

Zhang et al. 2019a). Atmospheric studies show precisely that, similar to the universal biogeochemical cycles, MPs move cyclically from soil to water and air and fall back from the atmosphere to aquatic environments or the land (Figure 6.2). This phenomenon, which must have started with the invention of plastics in the nineteenth century, will continue for centuries as these minute synthetic particles will not decompose or fully degrade for many years.

Spatially, Arctic and Pyrenees studies illustrate the invasion of atmospheric MPs into remote areas that people believed were unpolluted. These studies have demonstrated an important aspect of the transport of atmospheric MPs. The study of the French Pyrenees reported relative daily counts of 249 fragments, 73 films, and 44 fibres per m^3 in pristine mountain catchments. As revealed by air mass trajectory analysis, these came from nearby densely populated areas up to 95 km north. This transportation could lead to the deposition of MPs in any land or aquatic environment (Allen et al. 2019b; Bergmann et al. 2019; Zhang et al. 2019a). Considering the shape and the transport of MPs, some think that films have more surface area than fragments and may travel further, but that has not yet been proven (Verla et al. 2019a).

The average abundance of atmospheric MPs varied greatly among different studied areas. In European cities, the mean MP abundance from dry and wet deposition has been found between 118 (Paris) and 275 (Hamburg) particles/m^2d (Dris et al. 2015, 2016; Klein and Fischer 2019). But in Dongguan city in China, the abundance of non-fibrous MPs and fibres ranged from 175 to 313 particles/m^2d in atmospheric deposition (Cai et al. 2017). The deposition flux of atmospheric MPs in Yantai (a coastal city) in China attained a maximum of 602 particles/m^2d (Zhou et al. 2017). A total of 2649 MPs were detected in 10 street dust samples in Tehran, and the minimum and maximum concentrations of MPs ranged from 83 ± 10 particles/30 g dry dust to 605 ± 10 particles/30 g dry dust (Dehghani et al. 2017). In a remote area of the Pyrenees Mountains, the result illustrates an average MP particle

deposition of 365 particles/m^2d (Allen et al. 2019b). Atmospheric MPs observed from urban cities to remote, pristine areas further indicate that MP pollution has become a global issue (Bank and Hansson 2019).

The quantity of suspended atmospheric MPs in Shanghai from filtered air ranged from 0 to 4.18 particles per m^3, with an average level of 1.42 ± 1.42 particles per m^3 (Liu et al. 2019b). Shanghai had a greater MP abundance than Paris, probably because it has more anthropogenic activities, is more congested with people, and has a higher industrialisation level (Zhang et al. 2020a).

Current research from China and other countries has shown a greater abundance of MPs in indoor air than in outdoor environments. In one study, indoor concentrations ranged between 1.0 and 60.0 fibres per m^3, while outdoor concentrations ranged between 0.3 and 1.5 fibres per m^3 (Dris et al. 2017). In China, outdoor atmospheric MP abundance has been reported as up to 4.18 particles per m^3 (Shanghai); and in Surabaya, Indonesia, it is up to 174 particles per m^3. In indoor dust samples from 39 major cities in China, MPs (detected PET) abundance ranges from 1550 to 120 000 mg/kg, with a median abundance of 26 800 mg/kg (Liu et al. 2019a). These findings show that indoor MPs may be an important source of atmospheric MPs and contribute to atmospheric deposition (Dris et al. 2017).

6.2.5 Effects of Climatic Conditions on MP Distribution

It has been shown that rainfall and snowfall might be decisive factors in atmospheric MP deposition (Dris et al. 2016; Allen et al. 2019b). Despite no significant quantitative correlation between the concentrations of fibres and the characteristic of the rain events (rainfall depth, intensity, etc.), total atmospheric fallout (TAF) during wet weather periods is always substantially more significant than during dry weather periods (Gasperi et al. 2018).

The speed of the wind influences MP dispersal in the atmosphere; when the speed is higher, a decrease in pollution concentrations is seen. Additionally, wind direction (parallel versus perpendicular to obstacles) and sedimentation of particles >2.5 mm play a role in MP distribution in air. Temperature is another factor, with lower temperatures increasing nucleation and condensation of particles, resulting in lower atmospheric concentrations (Facciolà et al. 2021).

Snow is considered a positive method of MP deposition (atmospheric particle scrounging), depositing atmospheric particulates in urban areas and on the sea or in Arctic regions. MPs and nanoplastics (NPs) were recently shown by Ganguly and Ariya (2019) (laboratory study) to be efficient cloud ice nuclei, which may explain the slight correlation between MP counts and snow events recorded by Allen et al. (2019a). The recent study by Bergmann et al. (2019) indicates that the deposition of MPs ranged from 190 to 154×10^3 particles per litre and $0–14.4 \times 10^3$ particles per litre in melted snow sampled from Europe and the Arctic, respectively. The authors suggested that this abundance (Bergmann et al. 2019) was four to seven orders of magnitude higher than concentrations in previous reports from Dongguan and Paris (Cai et al. 2017; Dris et al. 2017). A large proportion of this discrepancy could be due to significant methodology differences. Specifically, the variation limit of particle size was analysed (11 μm in the Arctic study, ~50 μm in Paris, and ~200 μm in Dongguan). Rainfall also appears to be an essential factor influencing the fallout flux.

6.2.6 Transport Pathways

Only a few atmospheric MPs studies have tested these particles' transport pathways or trajectories. In one study (Allen et al. 2019a), particle transport was greater than 100 km. This study used simplistic meteorological and particle settling velocity calculations and the well-known atmospheric Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) to examine dynamic atmospheric transport. These models could identify the potential source of an atmospheric pollutant and the atmospheric trajectory along which it may have travelled (distance, elevation, atmospheric mixing, etc.). Another study used HYSPLIT to consider the possible sources of atmospheric MPs (air mass sampling), creating back trajectories relative to the sample period (Liu et al. 2019c). These models are well established and used for atmospheric modelling of pollutants, particles, and gasses such as mercury, caesium, and dust and, as such, have great potential to be used for in-depth analysis of atmospheric MP transport (Zhang et al. 2020a).

6.2.7 Pollutants Associated with MPs

MPs contain a range of functional additives (stabilisers, flame-retardants, plasticisers, etc.), dyes, inert fillers (talc, kaolin, clay, calcium carbonate), and other fillers (glass). MPs are also a pollutant transport medium for other toxic elements. Reported toxic chemicals consisted of heavy metals and hydrophobic organic contaminants (HOCs). These are known as persistent organic pollutants (POPs) and include polyaromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), Dichlorodiphenyltrichloroethane (DDT), and hexachlorobenzene (Laskar and Kumar 2019; Verla et al. 2019a). These lethal chemicals become attached to MPs by adsorption and then are released by desorption, with the potential for toxicity and accumulation in the food chain (Verla et al. 2019a).

Table 6.1 summarises the sampling methods, detection techniques, total abundance, and characteristic features of atmospheric MPs detected in different countries.

6.3 Impact of Microplastics on Human Health and the Eco Risk

The chemical composition of plastic is the basis for defining plastic pollution (Hartmann et al. 2019). A minimum of 45 different types of plastics are in commercial use, including PP, PE, PET, PS, polyurethane (PU), PVC, and PC (Li et al. 2016). The distribution of MP particles in the air is generally identified as a critical factor in understanding their atmospheric fate and transport and how those can affect human health and the environment (Wright et al. 2021). Other decisive factors in human exposure in indoor and outdoor environments include vertical gradient, higher pollution concentrations near the ground, and particle resuspension.

6.3.1 Impact on Human Health

Although it was previously thought that food was the primary pathway for MPs to get into the human body, current atmospheric research has shown that the main culprit is breathing air (Figure 6.3). Considering human exposure, the per capita intake of MPs through ingestion of food, water, and dust and inhalation of air is about 74 000–121 000 items annually (Cox et al. 2019). For humans, during exposures such as inhalation, particles with an aerodynamic diameter <10 μm (PM_{10}) and ≤2.5 μm ($PM_{2.5}$) are considered the most significant respiratory and cardiovascular hazards (US EPA 2019; World Health Organization 2006), and diameter is, therefore a fundamental property to characterise and measure these particulates considering the human health implications. Atmospheric particulate matter (PM) with aerodynamic diameters (D) ≤100 μm are considered inhalable. Further, particles ≥10 μm can be deposited in the nasopharyngeal airway. Characterising and quantifying the concentrations of PM relative to D thus represents an essential information source for assessing human inhalation exposure (Wright et al. 2021). In principle, the number of MPs in the atmosphere, and particle size less than 10 μm, could significantly determine human exposure and risk (Wright et al. 2021). Fibrous MPs in the air can enter the body through the mouth, nose, or skin (Enyoh et al. 2019). Fibrous MPs with a length greater than 5 mm, diameter less than 3 mm, and aspect (length-to-diameter) ratio greater than 3–1 does not meet the criteria for airborne fibres (World Health Organization 1997). Researchers assume that if the MPs are small enough to enter cells or tissues, they may irritate just by being an alien body; or if fibres are long and thin – that is, like asbestos – they can inflame lung tissue and lead to cancer (Lim 2021).

The controlled exposure studies performed on cell lines (human cells and rodents) observed that MPs of size <10 μm can move from the gut to the circulatory system and accumulate in the liver, kidney, and brain (Shelver and Banerjee 2021). The minutest particles (<0.1 μm) can cross cell membranes, the placenta, and the blood–brain barrier (Prietl et al. 2014). More prominent MPs are likely to be excreted through faeces or mucociliary clearance after lung deposition. MPs' size, shape, dose, surface functionalisation, charge, and hydrophobicity can affect their uptake, translocation, and accumulation within the human body (Shelver and Banerjee 2021). The toxicity of MPs increases with a decrease in size (Banerjee and Shelver 2021). The accumulation of plastic fibres

Table 6.1 Characteristics of atmospheric microplastics reported in different countries.

Region/country	Sampling method	Analysis	Total abundance	Shape	Colour	Polymer	Reference
Nagpur, India	High-volume air samplers using PTFE filter papers	Stereomicroscope, fluorescence microscope, FTIR	50–120 particles per day	Fibre, fragment, film, sphere	Transparent, white, orange, yellow, red, brown, black, grey, green, blue	Low-density PE, rayon, rubber fibre, PS, polyaniline, polyolefin, chlorinated PVC	Narmadha et al. (2020)
Humber, United Kingdom	Passive sampling using PVC bottles	μ-FTIR	3055 ± 5072 particles/m^2 day	Film, fibre, fragment	ND	PE, nylon, ethylene vinyl acetate, PET, PMMA, PP, polypropylene-polyethylene co-polymer, PS, polytetrafluoroethylene, PU	Jenner et al. (2022)
Northwestern South China Sea	Active atmospheric sampler; GF/A glass microfiber filter; passive sampler	Stereomicroscope, FTIR	0.035 ± 0.015 particles per m^3	Fibre, granule, film, fragment, foam	White, blue, red, brown, black, transparent	PES, PP, rayon, PE, PA, PS, phenoxy resin	Ding et al. (2021)
Guangzhou, China	Passive sampler; stainless-steel sieve	Stereomicroscope, eyepiece micrometre, μ-FTIR	51–178 particles/m^2 day	Fibre, fragment, film, microbead	Transparent, white, blue, red, green, grey	PET, PAN, PP, PA, PS, alkyd, epoxy resin, poly (styrene: acrylonitrile: butadiene)	Huang et al. (2021)
Dongguan, China	Sampling device equipped with a glass bottle	μ-FTIR, SEM	175–313 particles/m^2 day	Fibre, foam, fragment, film	ND	PE, PP, PS	Cai et al. (2017)
Shanghai, China	Active suspended particulate sampler	Stereomicroscope, μ-FTIR	1.42 ± 1.42 particles per m^3	Fibre, fragment, granule	Black, blue, red, transparent, brown, green, yellow, grey	PET, PE, PES, PAN, poly(*N*-methyl acrylamide), rayon, EVA, epoxy resin, alkyd resin	Liu et al. (2019b)
Hamburg, Germany	Bulk precipitation samplers	Fluorescence microscope, μ-Raman spectroscopy	136.5–512.0 particles per m^2/day	Fibre, fragment	ND	PE, EVA co-polymers, Teflon, PVA	Klein and Fischer (2019)

(*Continued*)

Table 6.1 (Continued)

Region/country	Sampling method	Analysis	Total abundance	Shape	Colour	Polymer	Reference
South-East Queensland, Australia	Dry sweeping	ASE, Pr-GC/MS	Rural location: 0.53 ± 0.16 mg/g Rural residential: 0.80 ± 0.49 mg/g Residential: 0.68 ± 0.20 mg/g Industrial: 2.4 ± 0.55 mg/g Traffic: 1.2 ± 0.70 mg/g City: 5.9 ± 3.1 mg/g	ND	ND	PP, PS, PET, PVC, PMMA, PE	O'Brien et al. (2021)
Paris, France	Pump and fibre GF/A Whatman filters	Stereomicroscope, FTIR coupled with ATR	Indoor: 1.0–60.0 fibres per m^3 Outdoor: 0.3–1.5 fibres per m^3	Fibre	ND	Nylon, PP	Dris et al. (2017)

ASE, accelerated solvent extraction; ATR, attenuated total reflectance; EVA, ethylene-vinyl acetate; FTIR, Fourier transform infrared spectroscopy; ND, not done; PA, polyamide; PAN, polyacrylonitrile; PE, polyethylene; PES, polyester; PET, polyethylene terephthalate; PMMA, polymethyl methacrylate; PP, polypropylene; Pr-GC/MS, pyrolysis gas chromatography–mass spectrometry; PS, polystyrene; PTFE, polytetrafluoroethylene; PU, polyurethane; PVA, polyvinyl acetate; PVC, polyvinyl chloride; SEM, scanning electron microscopy; μ-FTIR, micro-FTIR.

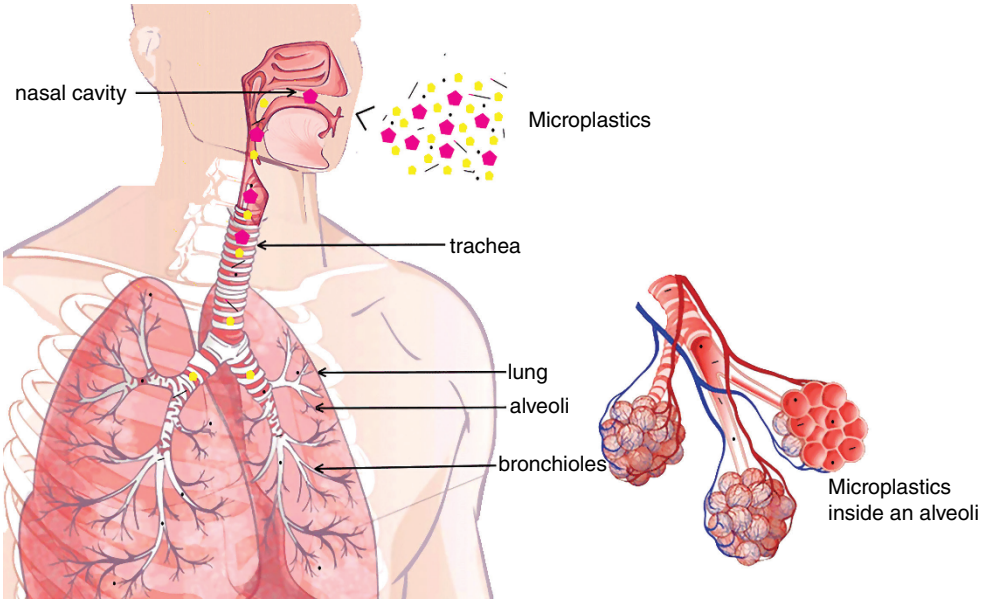

Figure 6.3 Atmospheric microplastics: human exposure through breathing air. *Illustration:* Ms. W.M.S.N. Bandara.

in the lungs was first reported in 1998, with 87% of 114 malignant and non-neoplastic lung specimens containing MPs (Pauly et al. 1998). It is proposed that MPs can accumulate in lung tissues and contribute to adverse health outcomes, leading to cancer. Similar to the 2.5 µm airborne particulate matter ($PM_{2.5}$), MPs should be considered in future monitoring studies and exposure assessments. *In vitro* tests have found plastic fibres to be highly durable in physiological fluid: polypropylene, polyethylene, and polycarbonate fibres showed almost no dissolution or changes to surface area and characteristics in synthetic extracellular lung fluid after 180 days. The result suggests the durability of the plastic fibres and the likeliness of persistence in the lungs (Law et al. 1990). Biopersistence is also connected to length, longer fibres cannot be efficiently cleared from the lungs (Warheit et al. 2001).

By exposing human cell lines to MP additives such as phthalates, bisphenols, and organotins, it was shown that these MPs cause adverse effects through the activation of nuclear receptors; peroxisome proliferator-activated receptors (PPARs) a, b, and g; and retinoid X receptor (RXR), leading to oxidative stress. Further, these MPs cause cytotoxicity, immunotoxicity, thyroid hormone disruption, and altered adipogenesis and energy production (Kannan and Vimalkumar 2021).

Many researchers (Dris et al. 2015, 2017) highlighted the presence of MPs in the urban atmosphere and their abundance, sources, pathways, and effect on humans. Currently, because MPs can be inhaled and are a matrix that other pollutants (mercury or PAHs) may attach to, these are considered to be an emergent component of air pollution (Wright and Kelly 2017; Gasperi et al. 2018; Liu et al. 2019a; Rochman et al. 2019). Of particular concerns are MPs in road-deposited dust that enters the human body via ingestion and inhalation. In humans, to estimate the potential health risk of ingested MPs, the number of daily and yearly ingested MPs should be counted. A study conducted on dust ingestion in Tehran, Iran, outlines the facts about exposure during outdoor activities and working areas with highly abundant MPs. The estimated intake of MPs ranged from 107 to 736 particles per year for adults in standard exposure scenarios and somewhat higher (353–2429 particles per year with a mean of 1063 particles per year) in acute exposure. Each child ingests 644 and 3223 particles per year in typical and acute exposure scenarios via ingestion, meaning road dust is a significant source of MP contamination in cities (Dehghani et al. 2017). Potentially vulnerable segments of the population are at risk, such as children, as their digestive systems are more susceptible to adverse health effects from environmental contaminants. Children's

yearly acute intake of MPs was approximately three times higher than that of adults, implying a higher potential risk of MP ingestion in children. Furthermore, workers involved in road construction, other people who work in outdoor areas, and pedestrians are directly at risk from MPs in street dust (Dehghani et al. 2017). MP particles (>100 μm) are shown to be biopersistent and to pass the gastrointestinal tract epithelium (Wright and Kelly 2017).

Human exposure to MPs, especially dust ingestion, can be estimated based on the atmospheric MP concentration. According to exposure models, the amount of MPs inhaled by humans ranged from 6.5–8.97 μg/kgBW/day. In infants and toddlers, this quantity is 3–50 times higher than in adults (Zhang et al. 2019c; Wang et al. 2021). Prata (2018) estimated the average per capita inhalation exposure to MPs at 26–30 particles daily. But some observed that the inhaled amount of airborne MPs could be as much as 272 particles per day (Vianello et al. 2019). Approximate human inhalation and dust ingestion exposure to MPs is a few milligrams per day. However, many factors can influence the inhaled quantities of MPs, including the types of textiles and personal care items used and other indoor environmental factors (such as ventilation); to reach a complete conclusion, further studies are needed (Prata et al. 2019). A human biomonitoring study reported bioresistant and biopersistent cellulosic and plastic fibres in pulmonary tissues (Pauly et al. 1998) as early as the 1990s, suggesting that airborne MPs can deposit or accumulate in the lungs. Fibrous particles of less than 10 μm in size are stated to deposit in the lungs (Gasperi et al. 2018). Alveolar macrophages engulf MPs; particles 15–20 μm in size are toxic (to macrophages) and ultimately enter the circulatory and lymphatic systems (Vethaak and Leslie 2016). MPs can induce an inflammatory response, cytotoxicity, and genotoxicity in lung tissues (Donaldson et al. 2000).

Further, occupational exposure to airborne MPs among workers in synthetic mills has been associated with respiratory illnesses (Prata 2018). Long-term MP exposure has led to lung diseases, including asthma and pneumoconiosis (Prata 2018). Although both MPs and NPs can reach the alveolar surface, the latter can pass into the bloodstream, overcoming the pulmonary epithelial barrier. Despite the low reactivity, the number of surface area atoms per unit mass is high in MPs and NPs, greatly enhancing the surface area for chemical reactions with bodily fluids and tissues in direct contact with them. This fact was confirmed with PVC and flock workers, who are prone to persistent inflammatory stimulation, leading to pulmonary fibrosis or even carcinogenesis (Facciolà et al. 2021).

Simplistic modelling has estimated that approximately 7665 particles of MPs are inhaled annually by people in Shanghai, China in outdoor environments (Liu et al. 2019b). Meanwhile, indoor dust is a non-negligible source of human exposure to MPs, accounting for a geomean daily intake of 17 300 ng/kg-BW (average body weight) of PET MPs in children of major Chinese cities (Liu et al. 2019a). Theoretically, most inhaled MP fibres could be removed by mucociliary clearance; however, some may persist in the lungs, causing localised biological responses, including inflammation, especially in individuals with compromised clearance mechanisms (Wright and Kelly 2017; Gasperi et al. 2018). The greatest exposure to airborne MPs is from working environments and not the home. Based on the literature, workers in two industries – the synthetic textile industry and vinyl chloride (VC) and PVC industries – were evaluated to determine the impact of these fibres on their respiratory health (Facciolà et al. 2021). A recent study described another source of airborne ultrafine plastic particles in the workplace: these were released by 3D printers, which use thermoplastics such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) (Zhang et al. 2019b). Refer to the review article by Facciolà et al. (2021) to learn more about the toxicity of atmospheric MPs and their impact on humans.

6.3.2 Eco Risk

Suspended atmospheric MPs may be an important source of MP pollution in the ocean (Liu et al. 2019c), but little is known about the processes governing the transport of MPs in the air (Allen et al. 2019a; Dris et al. 2017). The extent to which atmospheric fallout contributes to aquatic and terrestrial contamination is unknown. However, global simulations have quantified the atmospheric transport of MP particles produced by road traffic: tyre wear particles (TWPs) and brake wear particles (BWPs). Researchers found high transport efficiencies of these particles to remote regions (Evangeliou et al. 2020). From published data, 34% of emitted coarse TWPs and 30% of emitted coarse BWPs (100 kt/yr and 40 kt/yr, respectively) were deposited in the world's oceans, suggesting that direct

deposition of airborne road MPs is likely to be the critical source for the oceans (Evangeliou et al. 2020). Atmospheric MPs falling into aquatic systems have the potential to harm plants and organisms: they can be uptaken by the biota, or their chemical constituents and physical characteristics can destroy the particular ecosystem.

A risk from MPs in street dust is the likelihood of them entering groundwater from urban runoff and eventually joining the aquatic food chain. MPs have a lower density (0.8–1.4 g/cm^3) than mineralogical dust (2.65 g/cm^3) (Hidalgo-Ruz et al. 2012). It is hypothesised that MPs in road dust dissolve in raindrops, increasing their densities. As a result, the bulk of the MPs dissolved in rain drift to earth and reach aquatic environments more quickly than other waste, posing environmental and health risks to marine fauna and flora. These fallen MPs can also alter the soil microbiota in terrestrial ecosystems.

The size of the MP is a significant factor in determining the item's interaction with biota and its environment (Besseling et al. 2017; Hüffer et al. 2017). Specific shapes or sizes may have more significant potential to cause physical harm to organisms, with smaller angular particles passing membrane barriers more easily than particles presenting regular surfaces or longer edges (Hidalgo-Ruz et al. 2012; Rochman et al. 2019). It is assumed that MPs of <50 μm are most likely to be ingested or resuspended in the atmospheric load and inhaled (Dehghani et al. 2017). MPs present in the environment can be consumed by organisms including species widely used in the human diet (Rochman et al. 2015; Prata 2018). It is interesting to note that MPs have even been found in the digestive tracts of vertebrates and invertebrates (Rochman et al. 2015; Auta et al. 2017; Ribeiro-Claro et al. 2017; Li et al. 2018; Prata et al. 2019).

The sorption of chemicals (e.g. PAHs, mercury) by MPs may become a threat to biota when ingestion occurs or through leaching and desorption of adsorbed and plastic composite chemicals. Associated contaminants such as PAHs desorb and lead to genotoxicity. Plastics and additives (dyes, plasticisers, PFAs, phthalates) cause reproductive toxicity, carcinogenicity, and mutagenicity (Wirth et al. 2008; Wright and Kelly 2017; Gasperi et al. 2018). Pollutants such as DDT and hexachlorobenzene could also be adsorbed into MPs (Laskar and Kumar 2019).

The interaction of MPs and toxic chemicals challenges the environment, as it has been associated with mutagenic, teratogenic, and carcinogenic effects (Verla et al. 2019b, 2019c). The impact of atmospheric MPs, their chemical components, and their adsorbed pollutants on the health of humans and ecosystems is unknown, but the potential influence of MPs and NPs is a concern (Wright and Kelly 2017; Lehner et al. 2019).

6.4 Strategies to Minimise Atmospheric MPs through Future Research

Systematic and coordinated research efforts are vital to enable evidence-based decision-making and develop efficient policy measures on the national, regional, and global scales. Cooperation between researchers from multiple disciplines, policymakers, authorities, civil and industry organisations, and the public is necessary for drafting rules and regulations. This further requires clear and informative communication processes and open and continuous negotiations among all participants. Researchers must pay attention to scientific excellence, outlining the facts precisely, sharing them, and giving precedence to areas vital for both research and policy, with the common goal of establishing and updating action plans for universal benefit (Lusher et al. 2021).

A correct understanding of the current status of atmospheric MPs is essential for comparing their characteristics with those collected from other environments such as water and soil. To ensure the legitimacy and accuracy of data derived from MP research and allow comparisons, researchers have identified the critical factors that are necessary for all field and laboratory studies: the nature of the equipment used for MP sampling; the extent and number of days spent on all sampling (representing the period); and the spatial location of the samples (site and altitude) (Zhang et al. 2020a).

Precipitation studies have highlighted the need for event-specific sampling, permitting atmospheric deposition from individual rain/snowfall events to be determined. Furthermore, it has been shown that atmospheric deposition need to be correlated to meteorological conditions and sampling duration when gathering data. This must be

considered in the study design and provided in future atmospheric MP research reporting. Studies based on wet and dry deposition are still ongoing, and most are pilot studies. They have not covered similar geographical areas. According to reviewers, most information on MPs is relate to isolated studies that sample only a single point in time for each site or station. Studies with repeated sampling to identify changes in MP occurrence over time are scarce (Bråte et al. 2020). The effect of seasonality, climatic changes, and biological phenomena (e.g. algal blooms) on MP occurrences and distribution across a range of spatial and temporal scales are the other areas that need further study (Lusher et al. 2021).

Research is needed to establish whether a predominant group of polymers occurs in atmospheric MP pollution and whether the polymer composition changes due to sample location and the distance particles travel. Studies also need to be conducted on the effect of pollutants adhering to MPs when these particulate matters interact with ecosystems and humans.

Another area that needs attention is data reporting, because no proper evaluation of it has been carried out. Particle size is an essential aspect of atmospheric MP analysis and research. Both length and diameter should be included when reporting on the presence of MPs since the diameter is crucial to breathability, whilst length plays a vital role in persistence and toxicity. The full spectrum of fibres (both natural and petrochemical-based structures) must also be considered. The potential of inhaling fibres must also be determined, and all potential impacts must be urgently identified (Gasperi et al. 2018). When concerning inhalation exposure to MPs, most reports were for particulates >10 μm. However, due to the associations between exposure to particles <10 μm and human health effects, researchers recommend that standard protocols be developed based on existing air-sampling methods capable of characterising MPs <10 μm (Wright et al. 2021). Additional research is needed to identify MP exposure rates, adherence to skin, toxicokinetic information about MP ingestion, and the relative contributions of different sources and pathways by which people are exposed to MPs. Studies on the significance of indoor air and dust as the primary sources of MP exposure in humans are scarce, and their relative contributions to cumulative exposure are unknown. Further research is needed to quantitatively assess exposure quantities of various types and sizes of MPs through air inhalation and dust ingestion, and the attendant health effects. Hence biomonitoring studies of MPs in lung biopsies will increase our understanding of the effects of MPs on respiratory health. Therefore, standard methods are necessary to determine MP levels in air and dust, and as such, the primary task is to regularise analytical techniques (Kannan and Vimalkumar 2021).

Atmospheric particle transport modelling is an important future focus of atmospheric MP transport research, with significant further research needs and challenges in defining and describing atmospheric MP transport dynamics. More research is needed on source-pathway-sink processes and transport parameters relative to meteorological conditions (Lusher et al. 2021). Further, studies are essential on the potential impact of atmospheric MPs on transport and deposition to remote areas and humans via food webs. This has now been recognised as an emerging global concern.

6.5 Conclusion

MPs are now recognised as atmospheric pollutants. Researchers have demonstrated the ubiquitous nature of MPs in the air by finding them in urban, rural, and remote atmospheres. As an atmospheric pollutant, there is significant potential for long-range transport and therefore an effect on locations far from the source. However, the interactions between MPs and other organic pollutants and metals in the atmosphere and their impacts on and interaction with the environment and the health of humans and ecosystems are virtually unstudied and need to be better understood. It is also challenging to interpret potential health risks using available information about atmospheric MPs due to inconsistencies in sampling, sample preparation, and analysis methods. Most studies have not been subjected to quality assessment and quality control (QA/QC) practices. As such, until standardised procedures are used to measure MPs in the air, it is challenging to come to conclusions about MPs in the atmosphere or the actual risk from atmospheric MPs to humans and the environment.

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